REMARKS

Claims 1, 3-4 and 7-8 are pending in this application. By this Amendment, claim 1 is amended. Reconsideration in view of the above amendment and following remarks is respectfully requested.

Entry of the amendments is proper under 37 CFR §1.116 since the amendments: (a) place the application in condition for allowance (for the reasons discussed herein); (b) do not raise any new issue requiring further search and/or consideration (since the amendments amplify issues previously discussed throughout prosecution); (c) satisfy a requirement of form asserted in the previous Office Action; and (d) place the application in better form for appeal, should an appeal be necessary. The amendments are necessary and were not earlier presented because they are made in response to arguments raised in the final rejection. Entry of the amendments is thus respectfully requested.

The courtesies extended to Applicants' representative by Examiner Bernatz at the telephone interviews held September 23 and September 24, are appreciated. The reasons presented at the interviews as warranting favorable action are incorporated into the remarks below and constitute Applicants' record of the interview.

The Office Action rejects claim 1 under 35 U.S.C. §112, first paragraph. As agreed during the telephone interview, the above-described amendment obviates the ground for the rejection. Accordingly, Applicants respectfully request that the rejection of claim 1 under 35 U.S.C. §112, first paragraph be withdrawn.

The Office Action rejects claims 1, 3-4 and 7-8 under 35 U.S.C. §102(e) over Hamada (U.S. Patent Publication No. 2001/0054681 A1). Applicants respectfully traverse this rejection.

In particular, Applicants assert that Hamada does not qualify as prior art. The priority date of Applicants' invention is August 2, 2000, and the effective filing date of Hamada is

June 20, 2001. Accordingly, Applicants assert that Hamada does not qualify as prior art. A verified translation of the priority document (JP 2000-234461) is attached to perfect Applicants' claim for priority. As such, Applicants respectfully request that the rejection of claims 1, 3-4 and 7-8 under 35 U.S.C. §102(e) be withdrawn.

The Office Action rejects claims 1, 3-4 and 7 under 35 U.S.C. §103(a) over Inoue et al. (U.S. Patent Publication No. 2001/0048643 A1) (Inoue) in view of Li (U.S. Patent No. 6,487,014 B2) and claim 8 under 35 U.S.C. §103(a) over Inoue in view of Li and further in view of Yamada (U.S. Patent No. 6,448,850 B1) and Hamada. Applicants respectfully traverse these rejections.

In particular, Applicants assert that neither Inoue nor Li, either alone or in combination, disclose, suggest or render obvious a magneto-optical body comprising two dielectric multilayered films and a magnetic film provided between the two dielectric multilayered films, wherein the two dielectric multilayered films comprise two types of dielectric films alternately laminated with each other regular in thickness and wherein the one dielectric film has a refractive index of three or higher, and the other dielectric film has a refractive index of SiO_2, as recited in independent claim 1.

The Office Action admits that Inoue fails to disclose dielectric layers meeting the refractive index limitations of claim 1 (Office Action, page 4, lines 14-15). Moreover, Li teaches stacked films of SiO_2 and Si which are only applied to the polarizing devices 130 and 132 (Figs. 13a-13b), but the stacked films of SiO_2 and Si are <u>not applied to the polarization rotating devices 134 and 136</u>, which correspond to a Faraday rotator (col. 13, lines 15-19). Applicants' invention, as recited in claim 1, has a large difference in refractive index between the dielectric layers, and the effect of that difference is to have a strong localization of light in the center of the magneto-optical body and to obtain a <u>large Faraday rotation angle</u>. Accordingly, the fact that Li teaches stacked films of SiO_2 and Si on polarization devices and

not on polarization-rotating devices 130 and 132 illustrates the fact that the combination of Inoue and Li would result in a structure clearly different from Applicants' claimed structure. Accordingly, Applicants assert that the combination of Inoue and Li does not disclose, suggest or render obvious the features of independent claim 1. As such, Applicants assert that independent claim 1 defines patentable subject matter.

For at least their dependence on allowable claim 1, Applicants assert that claims 3-4 and 7 also define patentable subject matter. Accordingly, Applicants respectfully request that the rejection of the claims under 35 U.S.C. §103(a) be withdrawn.

In view of the foregoing, it is respectfully submitted that this application is in condition for allowance. Favorable reconsideration and prompt allowance of claims 1, 3-4 and 7-8 are earnestly solicited.

Should the Examiner believe that anything further would be desirable in order to place this application in even better condition for allowance, the Examiner is invited to contact the undersigned at the telephone number set forth below.

Respectfully submitted,

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JAO:SPC:TMN/cmf

Attachments:
- Petition for Extension of Time
- Declaration
- Verified English translation of priority application

Date: November 28, 2003

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DECLARATION

I, Riichiro KOSUGE of Hanabusa Institute for the Protection of Industrial Property of 5th Floor, Shin-Ochanomizu Urban Trinity Bldg., 3-2, Kanda-Surugadai, Chiyoda-ku, Tokyo 101-0062, Japan do hereby solemnly and sincerely declare,

1. that I am acquainted with the Japanese and English language, and

2. that the English text attached hereto is a true translation of the following document:

Japanese Patent Application No. 2000-234461 filed on August 2, 2000

And, I make this solemn declaration conscientiously believing the same to be true and correct.

This 26th day of November 2003

The Hanabusa Institute for
the Protection of Industrial Property

R Kosuge

Riichiro KOSUGE

[Document Name] Specification

[Title of the invention]

MAGNETO-OPTICAL BODY AND OPTICAL ISOLATOR USING THE SAME

[Scope of demand for patent]

[Claim 1]

A magneto-optical body comprising:

two dielectric multilayered films in which two types of dielectric thin films having different optical characteristics are alternately laminated with regularity in thickness thereof, and a magnetic thin film provided between the two dielectric multilayered films; wherein one of the two types of dielectric thin films has a refractive index which is different from a refractive index of the other dielectric thin film.

[Claim 2]

The magneto-optical body according to Claim 1, wherein the one dielectric thin film has a refractive index of three or higher, and the other dielectric thin film has a refractive index of less than three.

[Claim 3]

The magneto-optical body according to one of Claim 1 and Claim 2, wherein the one dielectric thin film is Si, and the other dielectric thin film is SiO_2.

[Claim 4]

An optical isolator comprising the magneto-optical body according to one of Claims 1 to 3.

[Detailed explanation of the invention]

[0001]

[Field of industrial applicability]

The present invention relates to an optical isolator for use in an

optical fiber communication system, an optical measuring system and so forth, and more particularly, relates to a magneto-optical body and an optical isolator using the magneto-optical body.

[0002]

[Conventional technology]

In an optical fiber communication system having a semiconductor laser as a light source, in particular, a high-speed digital transmission or analog direct modulation type optical system, a reflection noise often causes serious problems to the system and device designs. The reflection noise is generated by the re-incidence of light, into the laser, that was reflected from connecting points of an optical connector, optical circuit components or the like used in an optical fiber circuit. In this case, an optical isolator is used in order to prohibit the re-incidence of reflected light. As basic functions, an optical isolator transmits light emitted from a semiconductor laser (light source) to a transmission line, such as an optical fiber, without loss, and shields reflected light from the optical fiber or the like to prevent light from returning to the semiconductor laser (light source).

[0003]

An optical isolator for use in an optical fiber communication system employs the Faraday effect (magneto-optic effect), the 45-degree rotary polarization of incident light. The optical isolator shields reflected light from a transmission line to prevent the light from returning to a light source while transmitting light emitted from the light source, such as a semiconductor laser, to the transmission line without loss.

[0004]

A conventional optical isolator for communication generally has a

polarizer, an analyzer, and a magneto-optical body that uses the Faraday effect (magneto-optical effect) and is provided between the polarizer and the analyzer.

FIG. 13, FIG. 14A and FIG. 14B show the structure of an optical isolator for communication, and the operation principles thereof. An optical isolator for communication shown in FIG. 13 is roughly composed of a polarizer 2A and an analyzer 2B, a Faraday rotator 1 (Faraday element, magneto-optical element, magneto-optical body) that is provided between the polarizer 2A and the analyzer 2B to rotate the plane of polarization of light by 45 degrees, and permanent magnets 3 for the application of a magnetic field.

[0005]

Incident light 101 from a forward direction shown in FIG. 14A is non-polarized light. However, after transmitting through the polarizer 2A, the light is composed only of a component in the polarization direction of the polarizer 2A, and is light 102. Subsequently, the light 102 transmits through the Faraday rotator 1, and the polarization direction thereof is rotated by 45 degrees, thus becoming light 103. If the polarization direction of the analyzer 2B were matched parallel to the polarization direction of the light that was rotated by 45 degrees, the light would pass through the analyzer 2B with minimal loss. On the other hand, as shown in FIG. 14B, only a component 106 in the polarization direction of the analyzer 2B, from light 105 reflected from an optical fiber or the like in a reverse direction, passes the analyzer 2B. The light is then made incident to the Faraday rotator 1 from the reverse direction. The light is further rotated by 45 degrees in the same direction as in case of the forward direction by the non-reciprocal

property that is unique to the Faraday effect. Accordingly, after passing through the Faraday rotator 1, the light becomes light 107 that is orthogonal to the polarization direction of the polarizer 2A, and is thus shielded so as not to return to the light source.

[0006]

A magneto-optical element as the Faraday rotator includes a single crystal thick film that is provided by thickening a material having a relatively high particular magneto-optical effect, such as yttrium iron garnet (YIG) and bismuth-substituted rare earth iron garnet (BiYIG), on a GGG (gadolinium-gallium-garnet) single crystal substrate by liquid phase epitaxial (LPE) growth. However, since this single crystal thick film is formed by the liquid phase epitaxial (LPE) growth, the film becomes too thick to keep the Faraday rotation angle of 45 degrees that is required to function as an optical isolator when being used as, for instance, an optical isolator. Moreover, the dimension thereof becomes too large to appropriately satisfy the above-noted requirements. Additionally, since the film is thick, problems are found such as large light absorption loss (decrease in transmission).

[0007]

Furthermore, many control parameters are required for the liquid phase epitaxial (LPE) growth, and in actuality the manufacturing technique is not good enough to grow a thick film. Furthermore, in order to provide 45-degree rotary polarization to a garnet thick film, a thick film grown by the liquid phase epitaxial (LPE) growth is polished to a predetermined thickness with precision and is further coated with AR, and is then cut into the size of an optical isolator. Bi-substituted garnet is several hundred μm in film thickness, and strict machining accuracy

is required. There is also a problem in that a GGG single crystal wafer for a substrate is extremely expensive.

[0008]

Under consideration of the above-noted problems of a magneto-optical element by the LPE, the present inventors have proposed an optical isolator. The optical isolator employs a magneto-optical body that is constructed to utilize the optical enhancement effect of a magneto-optical film so as to improve the magneto-optical effect, and is composed of the magneto-optical body, a polarizer and an analyzer.

The magneto-optical body is constructed by forming each magnetic layer and dielectric layer in an irregular thin thickness; or by forming two dielectric multilayered films in which magnetic bodies and dielectric bodies are alternately laminated with regularity in the thickness thereof, and an irregular multilayered part. In this case, as a polarizer and an analyzer, a calcite Rochon prism, a wedge-shape rutile single crystal or polarization beam splitter (PBS), or the like is used.

[0009]

FIG. 15 shows one embodiment of a magneto-optical body that is constructed to utilize the optical enhancement effect for the optical isolator proposed by the present inventors. This magneto-optical body 200 is a magneto-optical body of a $(SiO_2/Ta_2O_5)^n$/BiYIG/$(Ta_2O_5/SiO_2)^n$ multilayered film in which bismuth-substituted rare earth iron garnet (BiYIG) (magneto-optical thin film 207) is used at the center and a multilayered film of (SiO_2/Ta_2O_5) (dielectric multilayered film 210) and a multilayered film of (Ta_2O_5/SiO_2) (dielectric multilayered film 211) are provided as reflection layers at both sides of the magneto-optical thin

film, respectively. The BiYIG thin film (magneto-optical thin film 207) is formed by sputtering or the like herein.

[0010]

[Problems to be solved by the invention]

FIG. 16 shows the light transmittance and Faraday rotation angle of magneto-optical body of a $(SiO_2/Ta_2O_5)^{12}/BiYIG/(Ta_2O_5/SiO_2)^{12}$ multilayered film. As shown in the figure, the number of (SiO_2/Ta_2O_5) layers must be increased to obtain a large Faraday rotation angle. The magneto-optical body in the figure requires 49 layers. As the number of layers increases, the manufacturing cost thereof increases and process control also becomes difficult. Accordingly, a manufacturing yield decreases. Thus, the characteristics and a manufacturing yield of an isolator using such a magneto-optical body deteriorate.

[0011]

[Means to solve the problems]

A magneto-optical body according to a first aspect of the invention has two dielectric multilayered films in which two types of dielectric thin films having different optical characteristics are alternately laminated with regularity in the thickness thereof, and a magnetic thin film provided between the two dielectric multilayered films. One of the two types of dielectric thin films has a refractive index that is different from the refractive index of the other dielectric thin film.

[0012]

The refractive index of one dielectric thin film may be three or higher, and the refractive index of the other dielectric thin film may be less than three.

One dielectric thin film may be Si, and the other dielectric thin

film may be SiO_2.

[0013]

An optical isolator according to another aspect of the invention employs the magneto-optical body mentioned above.

[0014]

[Embodiment of the invention]

The present inventors discovered that light is more strongly localized at the center of a magneto-optical body. This magneto-optical body has two dielectric multilayered films in which two types of dielectric thin films having different optical characteristics are alternately laminated with regularity in the thickness thereof, and a magnetic thin film provided between the two dielectric multilayered films. The refractive index of one of the two dielectric thin films is made large and the refractive index of the other dielectric thin film is made small so as to provide a large difference between the refractive indexes of the two types of dielectric thin films. Accordingly, a large Faraday rotation angle may be obtained by strongly localizing light without increasing the layers of the dielectric multilayered films much.

[0015]

The embodiments of the present invention will be explained based on FIGs. 1 to 12. A magneto-optical body relating to a first embodiment of the present invention is roughly shown in FIG. 1. However, prior to the explanation thereof, a magnetic thin film and dielectric multilayered films constituting the magneto-optical body will be first explained based on FIGs. 3 to 7.

[0016]

Herein, it is considered that the magnetic thin film composing the

magneto-optical body is an optical film, and that light is made incident to a multilayered optical thin film 30 shown in FIG. 3 at θ_O. An incident angle to each layer is also regarded as θ_j. Then, the matrix method to calculate transmittance T and reflectance R may be expressed as in the following Formulas 1 to 10. When a film face is assumed as a semi-infinite plane, the amplitude reflection coefficient r and transmission coefficient t of a multilayered film composed of low-refraction layers (L layers) are as shown in the following Formula 1 and Formula 2, respectively.

$r = (\eta_m E_m - H_m)/(\eta_m E_m + H_m)$ Formula 1

$t = 2\eta_m/(\eta_m E_m + H_m)$ Formula 2

wherein E_m is an electric field vector, and H_m is a magnetic field vector.

[0017]

The electric field vector E_m and the magnetic field H_m are based on the following Formula 3.

$$\begin{pmatrix} E_m \\ H_m \end{pmatrix} = M \begin{pmatrix} 1 \\ \eta_s \end{pmatrix}$$

Formula 3

In the Formula 3, M is the product of matrices, and M is assumed to be $M_L M_{L-1} \ldots M_j \ldots M_2 M_1$. Thus, the jth matrix ($M_j$) of the thin film may be expressed by the following formula 4.

$$M_j = \begin{pmatrix} m_{11} & im_{12} \\ im_{21} & m_{22} \end{pmatrix} = \begin{pmatrix} \cos\delta_j & \frac{i}{\delta_j}\sin\delta_j \\ i\eta_j \sin\delta_j & \cos\delta_j \end{pmatrix}$$

Formula 4

[0019]

In the Formula 4, δj is assumed to be:

$\delta_j = (2\pi/\lambda)(n_j d_j \cos\theta_j)$. Formula 5

[0020]

In the Formula 5 above, $n_j d_j \cos\theta_j$ indicates an effective optical film thickness at the jth layer with the angle of refraction (θ_j). As shown in the following Formula 6, η in other formulas indicates the effective refractive index of a medium, a substrate and each layer.

$$\eta = \begin{cases} n/\cos\theta(p) \\ n\cos\theta(s) \end{cases}$$

Formula 6

[0021]

In the Formula 6 above, incident light is parallel (p) or vertical (s) to the plane of incidence. The angle θ is the angle of incidence (θ_o) at a medium, based on Snell's law shown in the following Formula 7.

$n_m \sin\theta_o = n_j \sin\theta_j$ Formula 7

[0022]

Furthermore, transmittance T and reflectance R may be expressed as the following Formula 8 and Formula 9, respectively.

$$T = \left(\frac{\eta_s}{\eta_m}\right)|t|^2$$

Formula 8

wherein η_s is the effective refractive index of a substrate, and η_m is the effective refractive index of an uppermost layer.

$$R = |r|^2$$

Formula 9

Herein, the phase thickness (δ_j) of the thin film to which light is made incident obliquely, is given by the following Formula 10.

$\delta_j = (2\pi/\lambda)(n_j d_j \cos\theta_j)$ Formula 10

It is understood from Formula 10 that the apparent optical film thickness ($n_j d_j \cos\theta_j$) varies along with the change in the angle of incidence.

[0023]

If the magnetic thin film is the ideal Fabry-PeΓrot resonator, the actual refractive index of the magnetic thin film,

N*

would be expressed by the following Formulas 11 to 14.

[0024]

In other words, when the magnetic thin film has a high refractive index, the actual refractive index of the magnetic thin film is expressed as in the following Formula 11.

$$n^* = n_H \left(\frac{m-(m-1)\left(\frac{n_L}{n_H}\right)}{(m-1)-(m-1)\left(\frac{n_L}{n_H}\right)+\left(\frac{n_H}{n_L}\right)} \right)^{1/2}$$

Formula 11

wherein n_H is the refractive index of a high-refraction layer, and n_L is the refractive index of a low-refraction layer.

In this case, the actual refractive index of the magnetic thin film to a first filter is expressed as in the following formula 12.

$n^* = (n_H n_L)^{1/2}$ Formula 12

[0025]

Moreover, when the magnetic thin film has a low refractive index, the actual refractive index of the magnetic thin film is expressed as in the following Formula 13.

$$n^* = n_L \left(\frac{m-(m-1)\left(\frac{n_L}{n_H}\right)}{m-m\left(\frac{n_L}{n_H}\right)+\left(\frac{n_L}{n_H}\right)} \right)^{1/2}$$

Formula 13

In this case, the actual refractive index to the first filter is expressed as in the following Formula 14.

$$n^* = \frac{n_L}{\left[1-\left(\frac{n_L}{n_H}\right)+\left(\frac{n_L}{n_H}\right)^2\right]^{1/2}}$$

Formula 14

[0026]

Accordingly, the examples of actual refractive indexes of the magnetic thin film to a first filter are as shown in Table 1 of FIG. 4.

[0027]

It is assumed that the magnetic thin film constituting the magneto-optical body is an optical film, and that light is made incident to the multilayer optical thin film shown in FIG. 3 at θ_o. In this case, the angle of incidence becomes small in accordance with Snell's law, and an actual optical film thickness becomes large based on $n_j d_j \cos\theta_j$. Therefore, the thicker the magnetic thin film becomes, the larger the Faraday rotation angle.

[0028]

A magneto-optical body is shown below in which, for example, SiO_2 (refractive index Mt = 1.415) and Si (Ms = 3.11) having a good light transmittance in an infrared light region are used as a low-refraction film and a high-refraction film, respectively. As a high-refraction film, Ge having good light transmittance in an infrared light region may also be used.

[0029]

One embodiment of a magneto-optical body constituting an optical isolator is a magneto-optical body of a $(SiO_2/Si)^n/BiYIG/(Si/SiO_2)^n$ multilayered film in which a bismuth-substituted rare earth iron garnet (BiYIG($(BiY)_3Fe_5O_{12}$)), BiTbIG($(BiTb)_3Fe_5O_{12}$), or cerium-substituted rare earth iron garnet (CeRIG) magneto-optical thin film (for example, BiYIG magneto-optical thin film herein) is used at the center and a (SiO_2/Si) multilayered film (dielectric multilayered film) and a (Si/SiO_2) multilayered film (dielectric multilayered film) are provided at both sides thereof, respectively, as reflection layers. The BiYIG thin film is formed by sputtering or the like.

Other methods, besides sputtering, such as deposition, CVD (Chemical Vapor Deposition) may also be applied to form the $(Si\ O_2/Si)^n$ multilayered film.

[0030]

The refractive index (Mt) of SiO_2 of the (SiO_2/Si) multilayered film and the (Si/SiO_2) multilayered film is smaller than the refractive index (Ms) of Si thereof. Each thickness Dt and Ds satisfies $Ms \cdot Ds = Mt \cdot Dt = \lambda/4$. For the BiYIG thin film, $Nm \cdot Dm$ is equal to λ or $\lambda/2$ (wherein Nm is a refractive index of BiYIG thin film, and Dm is a thickness of BiYIG thin

film).

[0031]

When the light of a specific wavelength is made incident to the magneto-optical body having the above-noted structure, light is strongly localized, showing a high magneto-optical effect and light transmittance. Moreover, optical thin films having specific optical characteristics are laminated at a predetermined thickness and an interference film for localizing light is formed at the center in the magneto-optical body, so that the construction of the $(SiO_2/Si)^n$ and $(Si/SiO_2)^n$ multilayered films should not be disarranged, in order to more strongly localize light.

[0032]

The characteristics of optical crystals will be explained in comparison with the state of ordinary electron crystals. Optical crystals have a wavelength region where light cannot propagate to a certain direction as electron crystals have a band gap at an energy level. This specific wavelength region is called a photonic band gap, and varies depending on crystal structures. FIG. 5 shows a photonic band gap (b) in comparison with an electron state (a).

[0033]

Moreover, disarrangement at one part of a periodic structure of crystals indicates that electron crystals have a defect, and light having a specific wavelength in a photonic band gap transmits therethrough. The distribution of a standing wave of the magneto-optical body is shown in FIG. 6. In the magneto-optical body shown in FIG. 6, light is strongly localized at the center thereof, which results in unique transmission properties and a strong magneto-optical effect. Additionally, it was realized, as shown in FIG. 7, that transmittance is high at a wavelength

where light is strongly localized.

[0034]

The present inventors verified with experiments that, in a magneto-optical body, light is strongly localized when light having a specific wavelength is made incident, and a high magneto-optical effect and transmittance are obtained. The magneto-optical effect further improves particularly when rare earth iron garnet having a large Faraday rotation angle is used as the magnetic film. This magneto-optical body, for instance, has two dielectric multilayered films, as reflection layers, in which multiple kinds of dielectric materials having different optical characteristics are alternately laminated with regularity in the thickness thereof. (An example is a SiO_2/Si multilayered film in which the refractive index (Mt) of SiO_2 is smaller than the refractive index (Ms) of Si and each thickness Dt and Ds satisfies $Ms \cdot Ds = Mt \cdot Dt = \lambda/4$.) The magneto-optical body also has a magnetic film (the thickness thereof is, for instance, λ or $\lambda/2$) provided between the two dielectric multilayered films.

[0035]

A magneto-optical body 300 relating to a first embodiment of the present invention will be explained below based on FIG. 1 herein. This magneto-optical body 300 includes two kinds of dielectric layers having different refractive indexes as reflection layers. The magneto-optical body 300 has the resonance wavelength of 1.31 μm. As a center layer, a $(BiY)_3Fe_5O_{12}$ garnet film (simply referred to as BiYIG film (magnetic thin film 307) hereinafter) is used. As reflection layers (two dielectric multilayered films 310, 311), n-layered films of a Si film 320 (one dielectric thin film) and a SiO_2 film 321 (the other dielectric thin film) are

used at both sides of the center layer, respectively.

[0036]

The reflection layers (dielectric multilayered films 310, 311) of the magneto-optical body 300 are symmetric to each other with respect to the center layer (magnetic thin film 307). Each dielectric film has a thickness of (wavelength of incident light (λ)/(4 $\times$ refractive index M of dielectric), and is alternately laminated. In other words, the dielectric films are laminated with regularity in the thickness thereof. The thickness of the SiO_2 film 321 is [1310/(4×1.415)] = 231 nm. The thickness of the Si film 320 is [1310/(4×3.11)] = 105 nm. Moreover, the center layer that is the BiYIG film 307, has a thickness which does not match the regularity of the reflection layers (310, 311), and the thickness is 298 nm. The wavelength of incident light (λ) is 1310 nm; the refractive index (Ms) of the Si film 320 (one dielectric thin film) is 3.11; and the refractive index (Mt) of the SiO_2 film 321 (the other dielectric thin film) is 1.415.

[0037]

For the magneto-optical body of a $(SiO_2/Si)^n/BiYIG/(Si/SiO_2)^n$ multilayered film, more specifically, the magneto-optical body 300 at n = 3, 4 and 5, the changes in transmittance and the Faraday rotation angles (θ_F) relative to the wavelength of incident light are shown in FIG. 2. In FIG. 2, vertical axes indicate the transmittance or the Faraday rotation angles (θ_F), and all the horizontal axes indicate the wavelengths of incident light (λ). As clearly seen from FIG. 2, the transmittance and the Faraday rotation angles (θ_F) have peaks at around 1310 nm of the wavelength λ.

[0038]

For the magneto-optical body of a $(SiO_2/Ta_2O_5)^{12}/BiYIG/(Ta_2O_5/SiO_2)^{12}$ multilayered film in the embodiment, each transmittance and Faraday rotation angle are compared herein.

[0039]

In the magneto-optical body 300 of this embodiment, refractive indexes are highly different between the two kinds of dielectric thin films (Si film 320 (one dielectric thin film) and SiO_2 film 321 (the other dielectric thin film). (The refractive index (Ms) of the Si film 320 is 3.11, and the refractive index (Mt) of the SiO_2 film 321 is 1.415.) Thus, the dielectrics (dielectric multilayered films 310, 311) having different refractive indexes are used as reflection layers, and the magneto-optical body has a high resonance Q (resonance level), thus more strongly localizing light at the center thereof and providing a high magneto-optical effect. Accordingly, large Faraday rotation angles are obtained with fewer layers. Thirteen layers at $n = 3$; 17 layers at $n = 4$; and 21 layers at $n = 5$.

[0040]

The layers of the dielectric thin films may be reduced in number by providing a large Faraday rotation angle, so that a manufacturing cost may be reduced. Additionally, process control becomes relatively easy, thus improving a manufacturing yield. Furthermore, the characteristics and manufacturing yield of an optical isolator using the magneto-optical body 300 may improve.

[0041]

Subsequently, the magneto-optical body of the embodiment of the present invention and the manufacturing method thereof will be

explained based on FIG. 8. On a substrate having a preferable light transmission property at working wavelengths, such as glass, a thin film having a high refractive index (for instance, Si thin film) is formed at a thickness of $\lambda/4$. A thin film having a low refractive index (for example, SiO_2 thin film) is then formed at a thickness of $\lambda/4$. This procedure is repeated n times, and a rare earth iron garnet film (BiYIG thin film) is formed. The rare earth iron garnet film is an amorphous layer and has no magnetism right after sputtering, so that it is necessary to crystallize garnet by a high-temperature thermal treatment. Thus, annealing is performed. Furthermore, a thin film having a low refractive index (for instance, SiO_2 thin film) is formed at a thickness of $\lambda/4$, and a thin film having a high refractive index (for example, Si thin film) is then formed at a thickness of $\lambda/4$. This procedure is repeated n times, thus forming the magneto-optical body of $(Si/SiO_2)^n/BiYIG/(SiO_2/Si)^n$ of the present invention.

[0042]

Moreover, the magneto-optical body of $(SiO_2/Si)^n/BiYIG/(Si/SiO_2)^n$ may be similarly formed by reversing the order of the Si thin films and the SiO_2 thin films and thus forming, from a substrate side, a thin film having a low refractive index (for instance, SiO_2 thin film) at a thickness of $\lambda/4$ and then a thin film having a high refractive index (for example, Si thin film) at a thickness of $\lambda/4$.

[0043]

However, in manufacturing the magneto-optical body using rare earth iron garnet, the rare earth iron garnet film is an amorphous layer and has no magnetism right after sputtering, so that garnet has to be crystallized by a high-temperature thermal treatment. On the other

hand, the periodic structure of the dielectric multilayered films is disarranged (damaged) by the high-temperature thermal treatment. Thus, it has been practically very difficult to manufacture the magneto-optical body using rare earth iron garnet.

In the embodiment, as shown in FIG. 9, an indium sheet 202 is placed on a water-cooled substrate holder 201, and a substrate (for instance, quartz glass) 203 is placed on the indium sheet 202. A glassy carbon 204 is set as a condensing plate on the substrate 203.

[0044]

A $(SiO_2/Si)^n$ layer 310 (one of the two dielectric multilayered films wherein n is the number of layers) in which Si films (dielectric material) and SiO_2 films (dielectric material) having different optical characteristics shown in FIG. 1 are alternately laminated with regularity in the thickness thereof, is laminated on the substrate 203. The Si films (dielectric material) and SiO_2 films (dielectric material) are formed of a material that is transparent in an infrared ray region and has high environmental stability. As the substrate 203, it is desirable to use a material that does not melt during the crystallization thermal treatment of the BiYIG thin film 307 by an infrared-ray introducing heater 220.

[0045]

The BiYIG thin film 307 (rare earth iron garnet) is then formed on the $(SiO_2/Si)^n$ layer 310. The crystallization thermal treatment is carried out on the BiYIG thin film 307 in this state by the infrared-ray introducing heater 220 as described below. Subsequently, on $(SiO_2/Si)^n$/BiYIG containing the crystallized BiYIG thin film 307, a $(Si/SiO_2)^n$ layer 311 (the other film of the two dielectric multilayered films) is formed, thus forming the magneto-optical body 300 of

$(SiO_2/Si)^n/BiYIG/(Si/SiO_2)^n$ shown in FIG. 1. The magneto-optical body 300 was formed by a multi-target RF magnetron sputtering device.

[0046]

The infrared-ray introducing heater 220, as shown in FIG. 9, has an infrared-ray generating member 221 to generate infrared rays, the glassy carbon 204 to condense infrared rays, a cooling mechanism 222 to cool the substrate holder 201, and a thermocouple 223 that is arranged on a surface of the glassy carbon 204 during heating and is used for monitoring temperature.

[0047]

During the crystallization thermal treatment of the BiYIG thin film 307 by the infrared-ray introducing heater 220, the substrate holder 201 is cooled, thereby cooling the $(SiO_2/Si)^n$ layer 310 through the substrate 203.

On the other hand, only the BiYIG thin film 307 is heated during the thermal treatment by the glassy carbon 204 that is heated by infrared rays, and the film is crystallized. In this case, infrared rays are intermittently irradiated (pulse heating).

[0048]

Since the $(SiO_2/Si)^n$ layer 310 is cooled as described above, the mutual diffusion of Si and SiO_2 of the $(SiO_2/Si)^n$ layer 310 is prevented. Accordingly, the periodic structure of the $(SiO_2/Si)^n$ layer 310 is not damaged. At the same time, the BiYIG thin film 307 is crystallized by the thermal treatment. Thus, the magneto-optical body 300 having effective magnetism and superior magneto-optical characteristics is manufactured.

[0049]

In this embodiment, the $(SiO_2/Si)^n$ layer 310 is cooled through the substrate 203. However, the $(SiO_2/Si)^n$ layer 310 may be directly cooled. During the thermal treatment by the infrared-ray introducing heater 220, the thermocouple 223 was placed in contact with the surface of the glassy carbon 204 for monitoring temperature. FIG. 10 shows the thermal treatment pattern. Moreover, when the crystallization thermal treatment was carried out by such heating method, the BiYIG thin film 307 which was amorphous right after the formation, was gradually crystallized at 850°C of thermal treatment temperature. The Faraday rotation angle thereof was also the same as the angle found when the film was heated and crystallized by a conventional electric furnace. Additionally, no surface roughening or cracks were found from the BiYIG thin film 307.

[0050]

On the other hand, $(SiO_2/Si)^n$/BiYIG was treated by the same heating method, and $(Si/SiO_2)^n$ was formed thereon, thus manufacturing a magneto-optical body of $(SiO_2/Si)^n$/BiYIG/$(Si/SiO_2)^n$. As a comparison, another magneto-optical body of $(SiO_2/Si)^n$/BiYIG/$(Si/SiO_2)^n$ was manufactured without the thermal treatment. Then, the transmission spectrums of each magneto-optical body were examined.

In case of the magneto-optical body with no thermal treatment, a photonic band gap appeared in the wavelength region of λ = 1000 to 1800 nm, and a sharp wavelength peak also appeared at λ = 1310 nm. Similarly, in case of the magneto-optical body with the heating treatment of the embodiment, a photonic band gap appeared in the wavelength region of λ = 1000 to 1800 nm, and a sharp wavelength peak also appeared at λ = 1310 nm. Thus, the waveforms of the transmission

spectrums were nearly the same between the magneto-optical body with no thermal treatment and the magneto-optical body of the embodiment of the present invention. This indicates that the periodic structure of the multilayered film of $(SiO_2/Si)^n/BiYIG/(Si/SiO_2)^n$ is hardly changed by the thermal treatment that is to crystallize the BiYIG thin film 307 with the irradiation of infrared rays by the infrared-ray introducing heater 220.

[0051]

For the magneto-optical body of $(SiO_2/Si)^n/BiYIG/(Si/SiO_2)^n$ that was manufactured by heating $(SiO_2/Si)^n/BiYIG$ and forming $(Si/SiO_2)^n$ thereon as mentioned above, a Faraday rotation angle was examined. According to the results (not shown), it was realized that the magneto-optical body 300 has a large Faraday rotation angle. Since infrared rays are intermittently irradiated (pulse heating) in the embodiment, the BiYIG thin film 307 may be crystallized more precisely.

[0052]

Moreover, since the glassy carbon 204 condenses infrared rays, the thermal treatment is carried out quickly. Moreover, the thermal treatment may be performed without providing the glassy carbon 204.

In the embodiment, the BiYIG thin film 307 is crystallized by infrared rays from the infrared-ray introducing heater 220 as an embodiment. However, the BiYIG thin film 307 may be crystallized by laser beams instead, as shown in FIG. 11 (second embodiment).

[0053]

In this second embodiment, the substrate 203 is set on the substrate holder 201 while the face of the substrate formed with $(SiO_2/Si)^n/BiYIG$ is placed upward. Laser beams are irradiated to the

$(SiO_2/Si)^n/BiYIG$ from a laser beam source 231, thus crystallizing the BiYIG thin film 307.

Moreover, since laser beams are intermittently irradiated (pulse heating), the BiYIG thin film 307 may be crystallized more precisely.

[0054]

The cooling mechanism 222 and the cooling treatment that are required in the first embodiment described above (FIG. 9), become unnecessary in the second embodiment. Accordingly, the manufacture becomes simple, and productivity increases with no cooling operation.

The magneto-optical body 300 in the two embodiments mentioned above has a high Faraday effect as described above, and can perform well when being used in various optical devices such as an optical isolator.

[0055]

In the present embodiments (first embodiment and second embodiment), the thermal treatment is carried out on the magneto-optical body 300, having two dielectric multilayered films in which multiple types of dielectric materials having different optical characteristics are alternately laminated with regularity in the thickness thereof, and a magnetic film provided between the two dielectric multilayered films. However, the target of the thermal treatment is not limited to this. The thermal treatment may be carried out, instead, to a magneto-optical having two regular multilayered parts in which dielectrics are alternately laminated with regularity in the thickness thereof, and a rare earth iron garnet magnetic film between the two regular multilayered parts. The above-noted dielectrics are composed of a dielectric multilayered film having a periodic structure in which multiple types of dielectric materials having different optical

characteristics are alternately laminated with regularity in the thickness thereof. Even in this case, the rare earth iron garnet magnetic film is crystallized without damaging the periodic structure of the dielectrics.

[0056]

In the present embodiments (first embodiment and second embodiment), the BiYIG thin film 307 is used as an embodiment. However, the present invention is not limited to this film, and other rare earth iron garnet thin films may be applied.

[0057]

An optical isolator may be constructed as shown in FIG. 12 by using the above-mentioned magneto-optical body (third embodiment).

The optical isolator shown in FIG. 12 is roughly composed of a polarizer 32A and an analyzer 32B, the magneto-optical body 300 (Faraday rotor, magneto-optical element) that is provided between the polarizer 32A and the analyzer 32B to rotate the plane of polarization of light by 45 degrees, and permanent magnets 33 to apply a magnetic field.

[0058]

In the third embodiment, the two types of dielectric thin films (Si film 320 and SiO_2 film 321 (see FIG. 1) have refractive indexes that are largely different from each other as described above. Thus, the magneto-optical body 300 has dielectrics (dielectric multilayered films 310, 311) having different refractive indexes, and has a high resonance Q (resonance level), thereby more strongly localizing light at the center thereof and providing a high magneto-optical effect. Additionally, a large Faraday rotation angle is obtained with fewer layers of the dielectric thin films.

[0059]

Moreover, since the layers of the dielectric thin films may be reduced in number to obtain a large Faraday rotation angle in the magneto-optical body 300, a manufacturing cost may be reduced. Additionally, a manufacturing yield may improve as process control becomes relatively easy. Accordingly, the optical isolator using the magneto-optical body 300 of the third embodiment (FIG. 12) has improved characteristics and manufacturing yield.

[0060]

[Effect of invention]

According to the present invention, one of the two types of dielectric thin films has a refractive index that is different from the refractive index of the other dielectric thin film, so that two dielectric multilayered films having different refractive indexes may be provided. Accordingly, light is more strongly localized at the center of a magneto-optical body, and a higher magneto-optical effect may be obtained. Additionally, a large Faraday rotation angle may be obtained with fewer layers of the dielectric thin films. Thus, a manufacturing cost is reduced as the layers of the dielectric thin films may be lessened. Moreover, process control becomes relatively easy, thus improving a manufacturing yield.

[0061]

Since the layers of dielectric thin films may be lessened, the manufacturing cost of a magneto-optical body is reduced. Process control also becomes relatively easy, thereby improving a manufacturing yield. Therefore, an optical isolator using the magneto-optical body has better characteristics and a higher manufacturing yield.

[Brief description of the drawing]

[Fig. 1]

FIG. 1 is a cross-sectional view of a magneto-optical body of a first embodiment of the present invention.

[Fig. 2]

FIG. 2 is a characteristic diagram, showing transmission wavelength spectrums and Faraday rotation angles of the magneto-optical body of the present invention.

[Fig. 3]

FIG. 3 is a diagram, showing the characteristics of incidence to a magnetic thin film.

[Fig. 4]

FIG. 4 is a table, showing the refractive indexes of a magnetic thin film.

[Fig. 5]

FIG. 5 is a diagram, showing a photonic band gap of optical crystals.

[Fig. 6]

FIG. 6 is a diagram, showing the pattern of a standing wave of the magneto-optical body.

[Fig. 7]

FIG. 7 is a diagram, showing relations between strongly localized wavelengths and transmittance.

[Fig. 8]

FIG. 8 is a diagram, showing the manufacturing method of the magneto-optical body in FIG. 1.

[Fig. 9]

FIG. 9 is a diagram, showing a set state of each member and an

infrared-ray introducing heater in the manufacturing method of FIG. 8.

[Fig. 10]

FIG. 10 is a diagram, showing a thermal treatment pattern in the manufacturing method of FIG. 8.

[Fig. 11]

FIG. 11 is a diagram to explain a second embodiment of the present invention.

[Fig. 12]

FIG. 12 is a diagram, showing an optical isolator relating to a third embodiment of the present invention.

[Fig. 13]

FIG. 13 is a diagram, showing one embodiment of a conventional optical isolator.

[Fig. 14]

FIG. 14A and FIG. 14B are diagrams, showing the operation principles of the optical isolator.

[Fig. 15]

FIG. 15 is a cross-sectional view of a conventional magneto-optical body.

[Fig. 16]

FIG. 16 is a diagram, showing the transmittance and Faraday rotation angles of a magneto-optical body.

[Document name] ABSTRACT

[Summary]

[Object]

This invention is to provide a magneto-optical body and an optical isolator using the same are provided at a lower manufacturing cost and with a higher yield.

[Means for the object]

The magneto-optical body includes dielectric multilayered films that are n-layered films of Si films having a refractive index (Ms) of 3.11 and SiO_2 films having a refractive index (Mt) of 1.415, as reflection layers provided at both sides of a magnetic thin film. By using the dielectric multilayered films having different refractive indexes for the reflection layers, a high resonance Q (resonance level) may be obtained, and light is intensely localized at the center. A high magneto-optical effect may be obtained, and a large Faraday rotation angle may be obtained with fewer layers of the dielectric thin films. A manufacturing cost is reduced, and process control also becomes easy, thereby improving a manufacturing yield.

FIG. 1

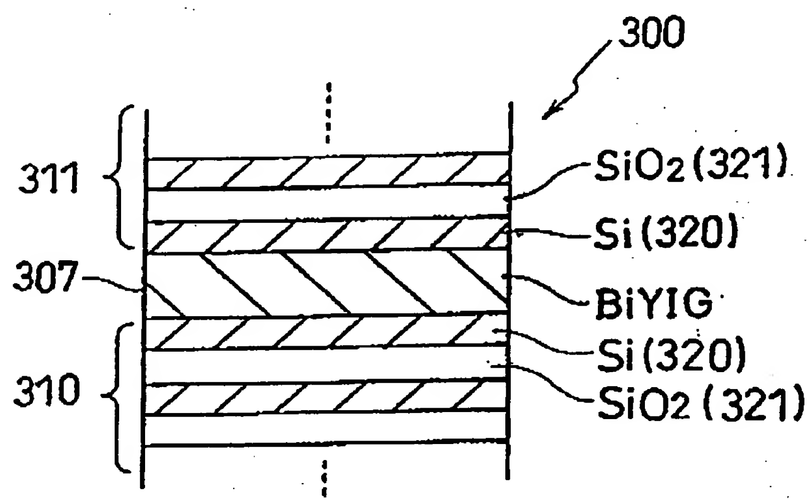


FIG. 2

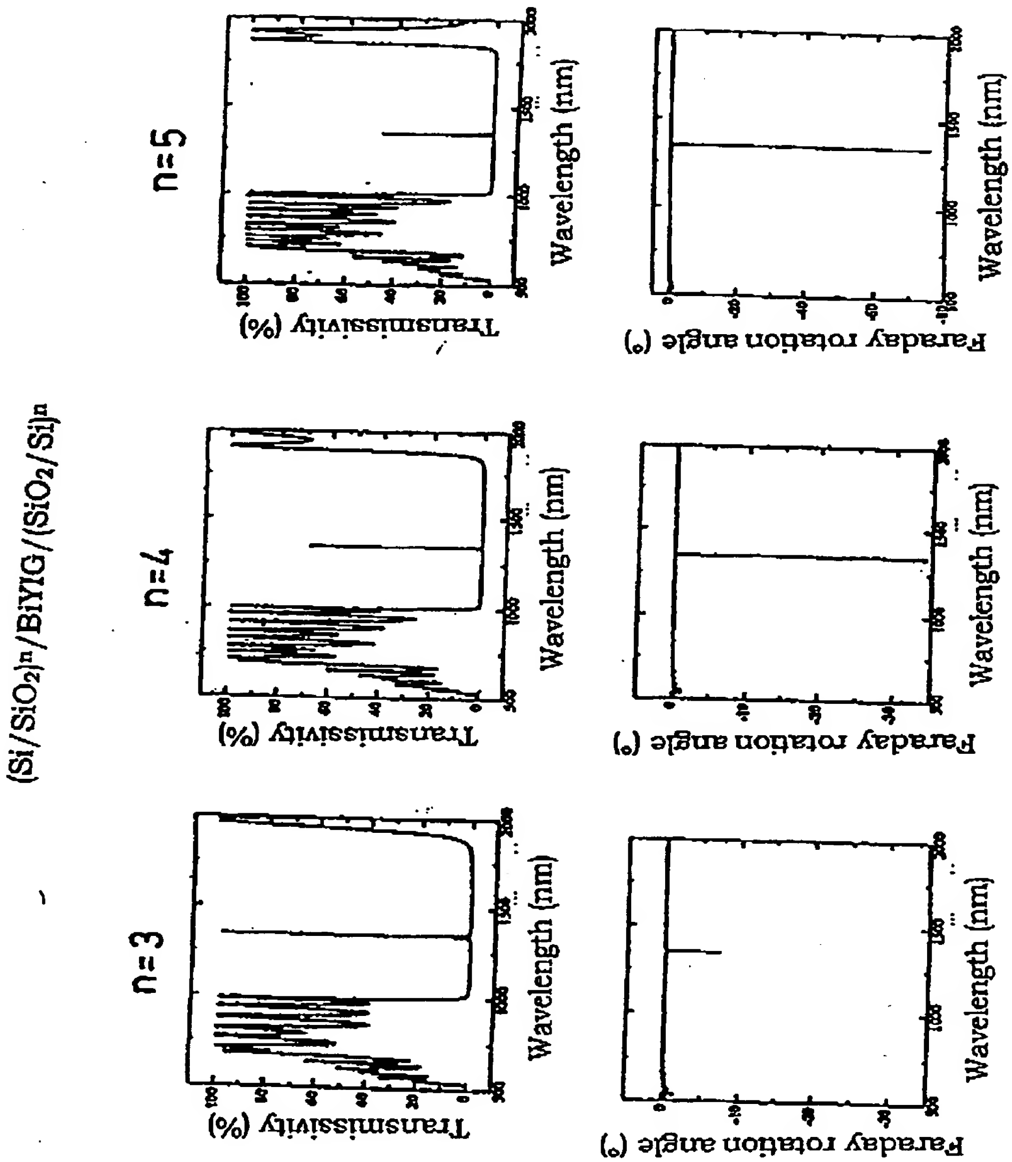

(Si/SiO2)n/BiYIG/(SiO2/Si)n
n=3
n=4
n=5
Transmissivity (%)
Wavelength (nm)
Faraday rotation angle (°)

FIG. 3

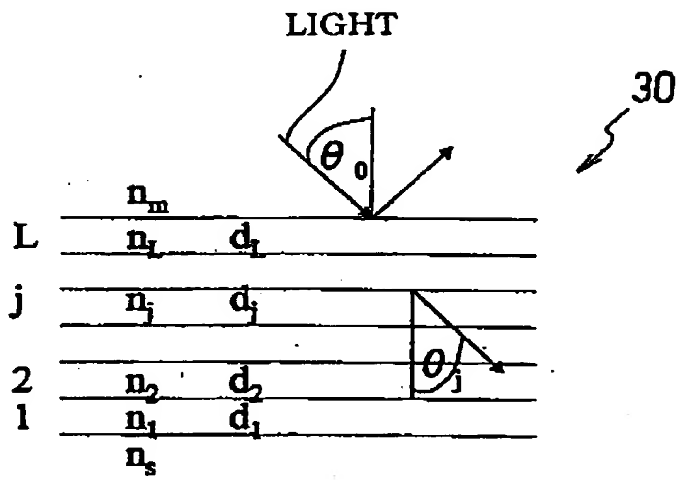


FIG. 4

	Refractive index of low-refraction layers	Refractive index of high-refraction layers	actual refractive index of the magnetic thin film in a high refraction	actual refractive index of the magnetic thin film in a low refraction
Example 1	1.415	2.35	1.823527	1.622657
Example 2	1.415	3.11	2.097773	1.631698

FIG. 5

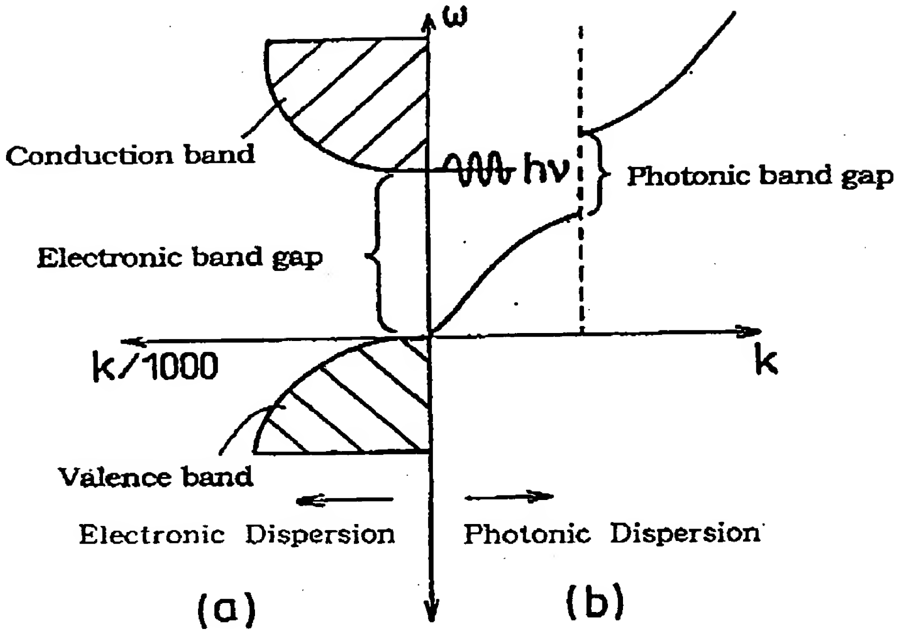

ω
Conduction band
hν
Photonic band gap
Electronic band gap
k/1000
k
Valence band
Electronic Dispersion
Photonic Dispersion
(a)
(b)

FIG. 6

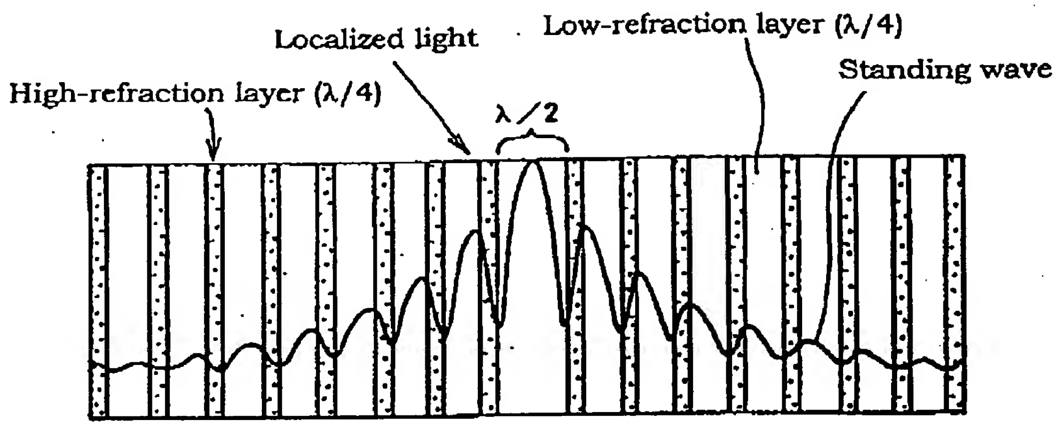

Localized light
Low-refraction layer (λ/4)
Standing wave
High-refraction layer (λ/4)
λ/2

FIG. 7

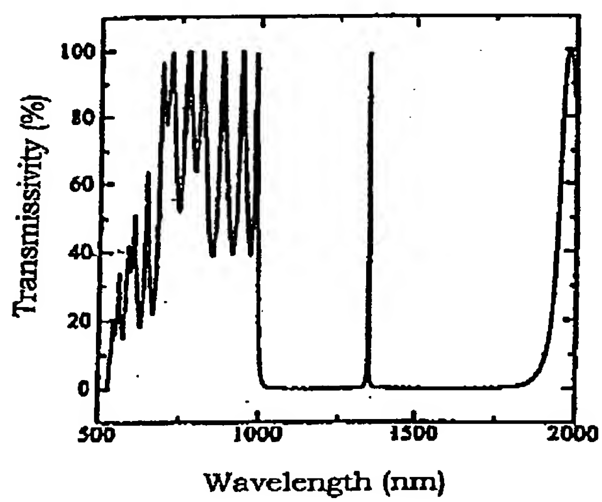

Transmissivity (%)
100
80
60
40
20
0
500
1000
1500
2000
Wavelength (nm)

FIG. 8

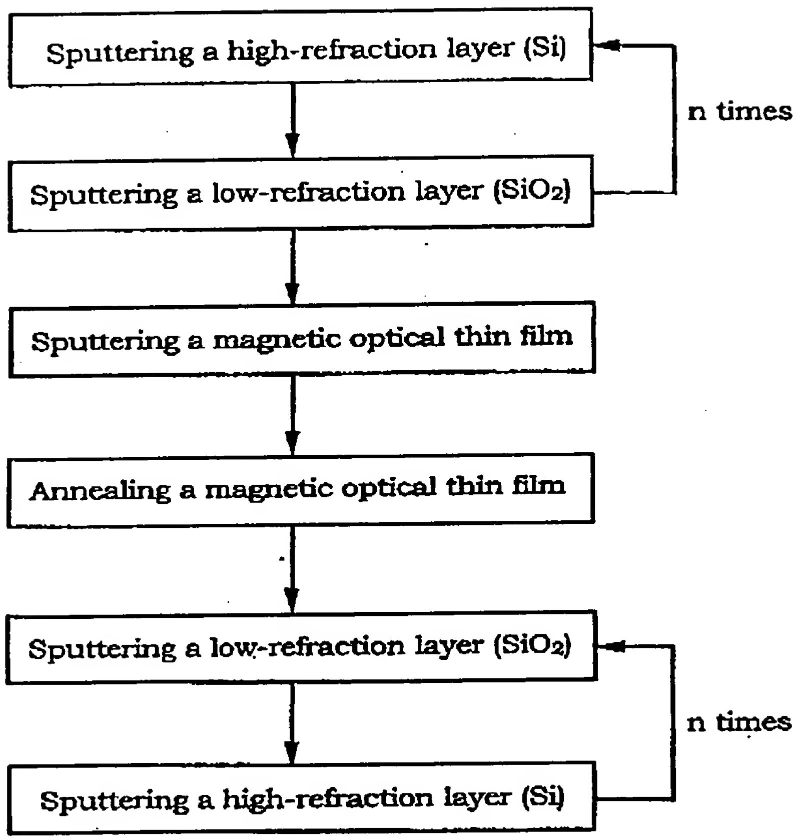

Sputtering a high-refraction layer (Si)
Sputtering a low-refraction layer (SiO_2)
n times
Sputtering a magnetic optical thin film
Annealing a magnetic optical thin film
Sputtering a low-refraction layer (SiO_2)
Sputtering a high-refraction layer (Si)
n times

FIG. 9

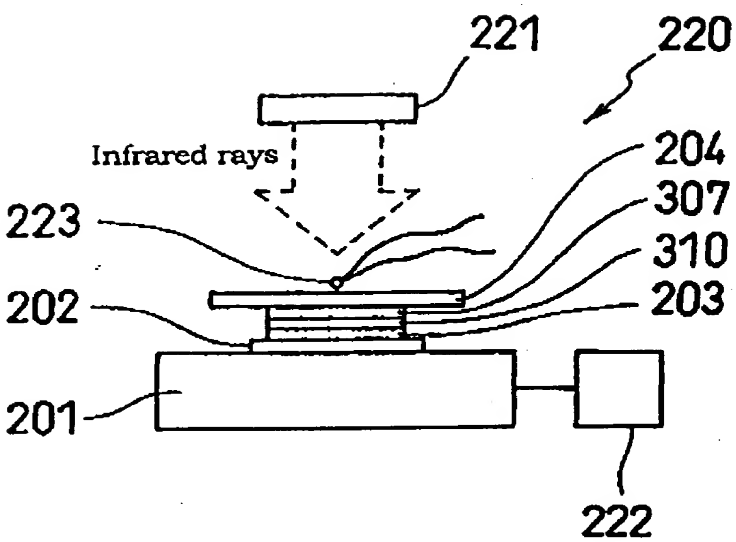
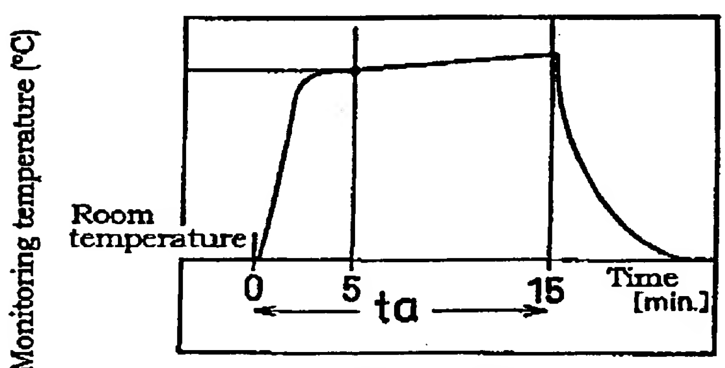


FIG. 10



Heating pattern

FIG. 11

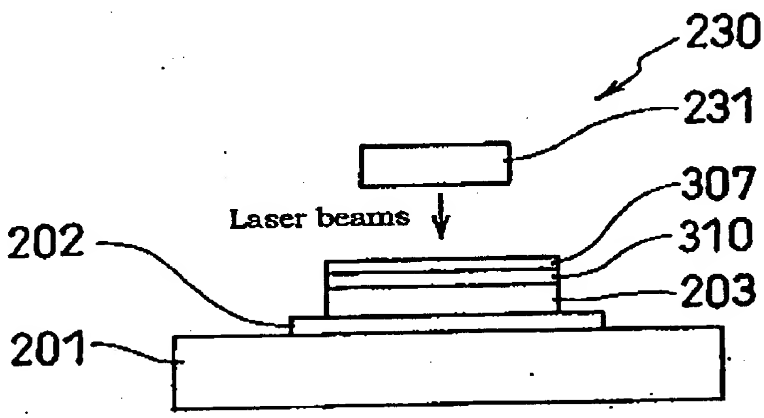


FIG. 12

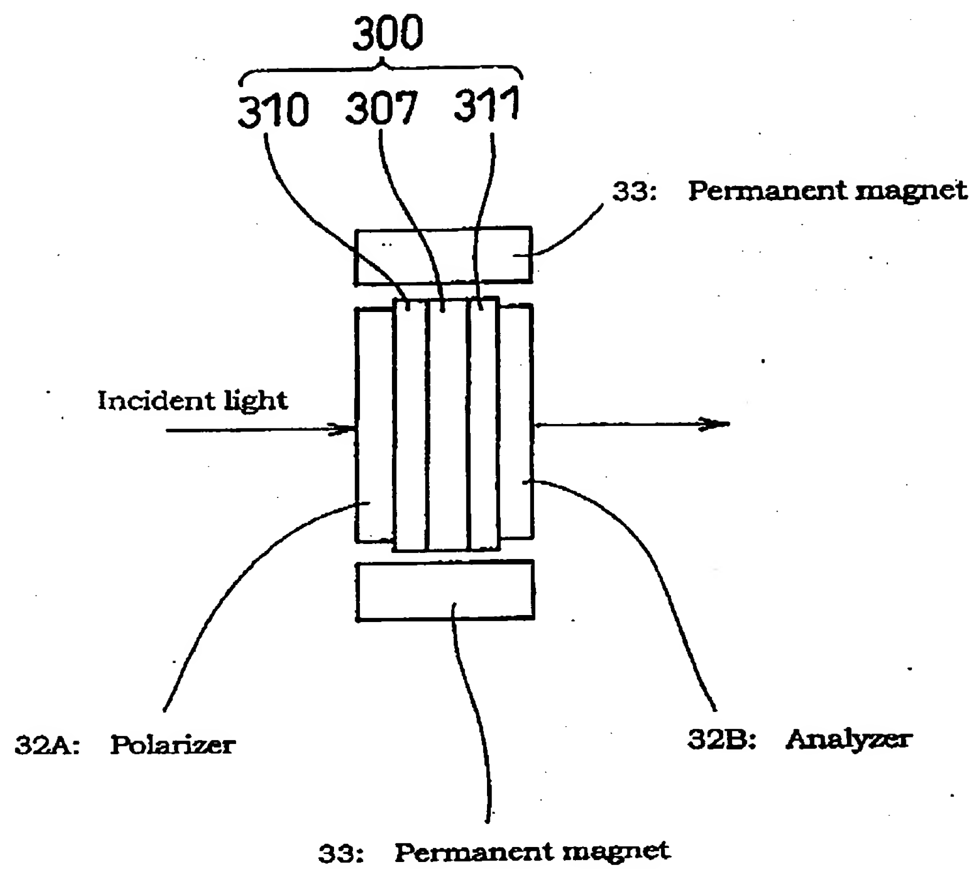

300
310
307
311
33: Permanent magnet
Incident light
32A: Polarizer
32B: Analyzer
33: Permanent magnet

FIG. 13

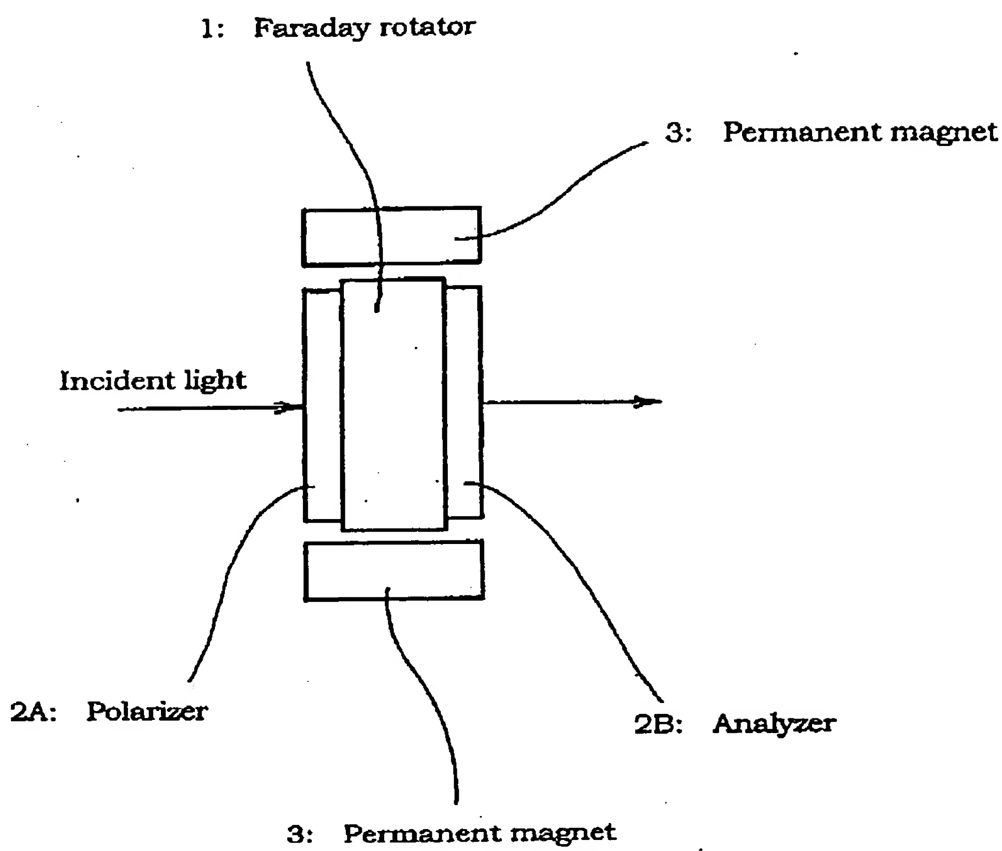

1: Faraday rotator
3: Permanent magnet
Incident light
2A: Polarizer
2B: Analyzer
3: Permanent magnet

FIG. 14A

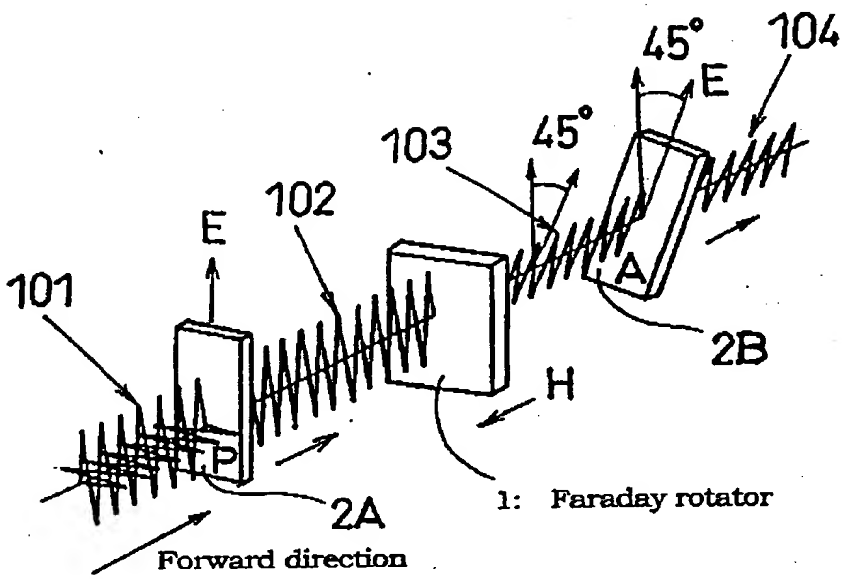


FIG. 14B

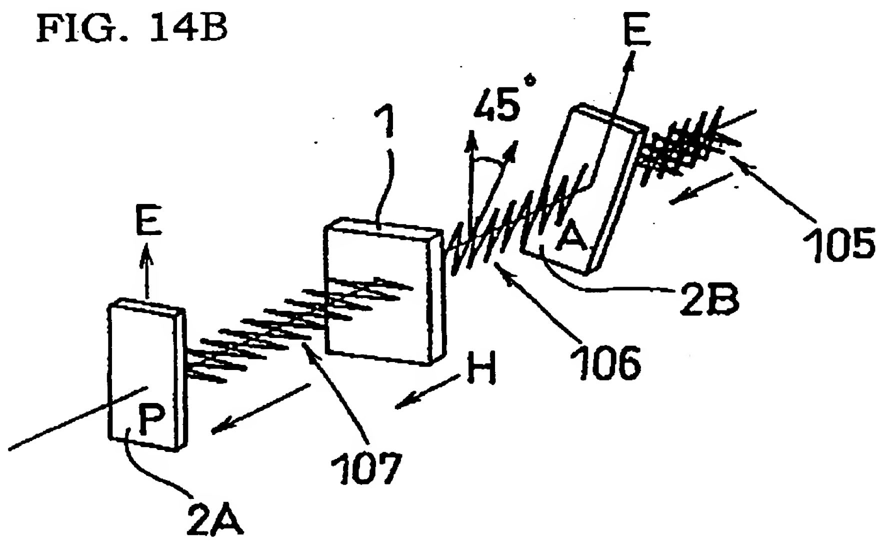


FIG. 15

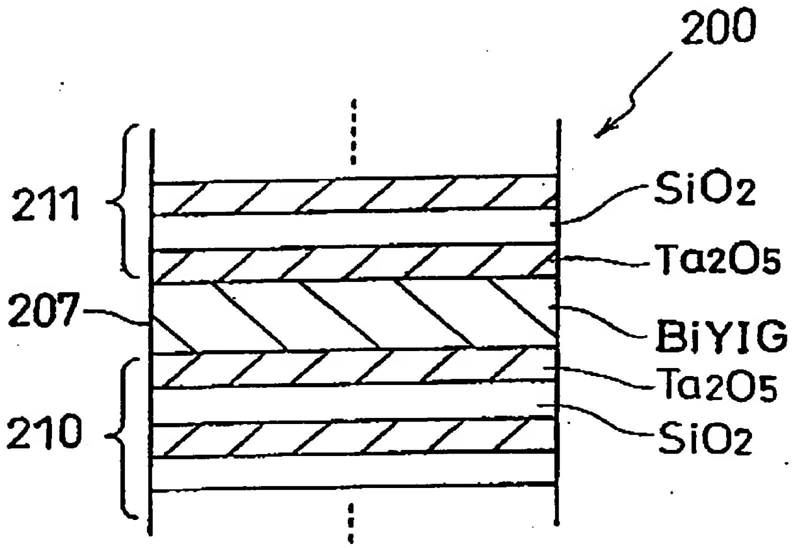


FIG. 16

Film Structure: $(SiO_2/Ta_2O_5)^{12}/BiYIG/(Ta_2O_5/SiO_2)^{12}$